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MAMBO 1.2 MILLIMETER OBSERVATIONS OF BzK-SELECTED STAR-FORMING GALAXIES AT z $\sim$ 2[1]

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ABSTRACT

We present MAMBO 1.2 mm observations of five *BzK*-pre-selected vigorous starburst galaxies at z $\sim$ 2. Two of these were detected at more than 99.5% confidence levels, with 1.2 mm fluxes around 1.5 mJy. These millimeter fluxes imply vigorous activity with star-formation rates (SFRs) $\approx$500–1500 $M_{\odot}\ yr^{-1}$, confirmed also by detections at 24μm with the MIPS camera on board of the Spitzer satellite. The two detected galaxies are the ones in the sample with the highest SFRs estimated from the rest-frame UV, and their far-IR- and UV-derived SFRs agree reasonably well. This is different from local ULIRGs and high-z submm/mm selected galaxies for which the UV is reported to underestimate SFRs by factors of 10–100, but similar to the average *BzK*–ULIRG galaxy at $z \sim 2$. The two galaxies detected at 1.2 mm are brighter in *K* than the typical NIR-counterparts of MAMBO and SCUBA sources, implying also a significantly different *K*-band to submm/mm flux ratio. This suggests a scenario in which $z \sim 2$ galaxies, after their rapid (sub)mm brightest phase opaque to optical/UV light, evolve into a longer lasting phase of *K*-band bright and massive objects. Targeting the most UV active *BzKs* could yield substantial detection rates at submm/mm wavelengths.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: starburst — cosmology: observations — submillimeter

1. INTRODUCTION

In the last few years, selection techniques at different wavelengths have revealed a variety of, at first glance, different high redshift source populations (e.g., Steidel et al. 1996; 2004; Smail et al. 1997; Kurk et al. 2000; Franx et al. 2003; Daddi et al. 2004a; Cimatti et al. 2004). Highly debated questions are how these objects are linked to each other; how much they overlap with each other; and what the evolutionary path is, if any, between them and with the different types of low redshift galaxies. Observations in the local universe are indicating (e.g., Thomas et al. 2005; Nelan et al. 2005) that the stars in massive early-type galaxies formed in general at high redshift, $z >> 1$, with short formation timescales, suggesting high peak star-formation rates (SFRs). Populations of high redshift galaxies, among those mentioned above, having large stellar masses and high SFRs have indeed also been found. However a detailed characterization of the formation of early-type galaxies is still missing.

Recently, Daddi et al. (2004b) presented a technique based on optical/near-IR photometry in the *B*, *z* and *K* bands that, at least to $K_{Vega} < 20$, allows to obtain virtually complete samples of galaxies at redshift $1.4 < z < 2.5$, including star-forming and passively evolving galaxies. This technique is reddening independent for $z \sim 2$ star-forming galaxies, that in $K < 20$ samples have SFRs estimated between $50-1000$ solar masses per year. These SFRs require large and possibly uncertain reddening corrections. The average long-wavelength emission properties of *BzK* star-forming galaxies (*sBzK*s hereafter) at $z = 2$ have been measured accurately by Daddi et al. (2005), finding that the typical *sBzK* is an Ultra Luminous Infra-Red Galaxy (ULIRG) with $SFR \sim 200-300\ M_{\odot}\ yr^{-1}$. As the *BzK* technique is substantially complete for $z \sim 2$ galaxies, one expect that also submm/mm selected galaxies (SMGs, see Blain et al. 2002 for a review) should fulfill the *BzK* criteria, as many of them lie at $z \sim 2$ (e.g., Chapman et al. 2005), and that the most active *sBzK* galaxies could actually be SMGs. In this letter we present observations with the 117–element *Max-Planck Millimeter Bolometer Array* (MAMBO; Kreysa et al. 1998) of five luminous ($K_{Vega} \lesssim 19$) *sBzK* galaxies, with high expected SFRs, based on their optical/UV properties. We report the detection of two of the five galaxies, and discuss some implications on the relation between *sBzK* and SMGs, and on the assembly process of massive galaxies at high redshifts. We assume a Salpeter initial mass function (IMF) from 0.1 to 100 $M_{\odot}$, and a cosmology with $\Omega_{\Lambda}, \Omega_M = 0.73, 0.27$, and $h = H_0[\mathrm{km\ s^{-1}\ Mpc^{-1}}]/100 = 0.71$ (Spergel et al. 2003).

2. SAMPLE SELECTION

We selected for MAMBO observations five bright $K_{Vega} <$ 19.2 mag *sBzK*-galaxies (see Table 1), taken from the 700 arcmin^2 wide 'Daddi-Field' at 14h (Daddi et al. 2000; Kong et al. 2005). All the targets had spectroscopic redshift identifications from deep VLT-VIMOS optical spectroscopy and sometimes VLT-SINFONI and/or Subaru-OHS/CISCO near-IR spectroscopy, as a part of our ongoing survey for *BzK* selected galaxies (Kong et al. 2005). The optical and near-IR spectroscopic observations will be presented elsewhere. Redshifts range from 1.6 to 2.8, and SFRs estimated

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TABLE 1
PROPERTIES OF THE *sBzK* GALAXIES OBSERVED WITH MAMBO.

Source (1)	RA (J2000) (2)	DEC (J2000) (3)	K (AB) (4)	BzK (AB) (5)	z_{spec} (6)	E$(B-V)$ (7)	SFR$_{UV}$ ($M_\odot/yr$) (8)	Mass ($10^{11}M_\odot$) (9)	S$_{1.2\ mm}$ (mJy) (10)	SFR$_{IR}$ ($M\odot/yr$) (11)	S$_{24\ \mu m}$ (μJy) (12)	Comments (13)
OBJ4415	14:48:35.35	08:52:27.0	20.92	1.61	2.53	0.49	177/140	2.8	0.55±0.54			Lyα; AGN-2
OBJ4193[a]	14:48:33.23	08:54:14.1	20.67	1.99	2.76	0.40	∼200	4.0	–0.26±0.58			Lyα; AGN-2
OBJ2742	14:49:20.50	08:50:52.3	20.84	0.02	2.16[b]	0.53	666/400	1.4	1.34±0.43[c]	700–1400	70±23	UV-abs/IR-em?
OBJ2426	14:49:28.96	08:51:52.9	20.76	0.05	2.37	0.59	546/1400	1.8	1.50±0.42	800–1900	200±50	UV-abs/IR-em
OBJ1901	14:49:41.38	08:59:50.5	20.58	0.68	1.60	0.33	186/140	1.7	0.54±0.43		79±25	UV-abs/IR-em

NOTE. — Col. (1): Object identification. Cols. (2)-(3): Optical/NIR coordinates. Col. (4): Total K-band magnitudes. Col. (5): BzK-color. $BzK \equiv (z-K)_{AB} - (B-z)_{AB}$ (Daddi et al. 2004b). Col. (6): Spectroscopic redshift. Col. (7): Colour excess: $E(B-V) = 0.25[(B-z)_{AB}+0.1]$, Daddi et al (2004b). Col. (8): Two SFR estimates are from the UV corrected 1500 Å luminosities (Daddi et al. 2004b) and from SED fitting, respectively. Col. (9): Stellar mass estimated from SED fitting; uncertainties are typically a factor of two. Col. (10): MAMBO "on–off" flux at 1.2 mm. Col. (11): SFRs estimate based on L_{IR}. Col. (12): MIPS 24 μm flux. Col. (13): Comments to the UV/optical spectra of individual sources. [a]: OBJ4193 is at the edge of the Subaru imaging data, photometry is less accurate. [b]: this redshift is lower quality, although supported by UV-spectrum and possible Hα detection. [c]: Excluding the first observing consisting of 7 scans under mediocre weather conditions would give $S_{1.2\ mm} = 1.57 \pm 0.46$ mJy ($\tau_{1.2\ mm} \leq 0.2$).

from the dust corrected UV luminosity range from ~ 150 to $\sim 1400\ M_\odot\ yr^{-1}$. Although the K-band brightest *sBzK* naturally tend to have fairly red average optical/UV colors, preference among sources with measured redshifts was given to objects with red $B-z$ colors, corresponding to large $E(B-V)$. The reasons for this preference are twofold: 1) optical redness might be an evidence for the presence of large amounts of dust, enhancing the chance of detections with MAMBO; 2) the red colors ensure these objects would rarely qualify for the $z=2$ criteria of Steidel et al. (2004), thus allowing to investigate to which extent vigorous starburst galaxies may be missed by surveys selected in the UV.

The field has been observed in the X-ray with XMM-Newton for 80 ks (Brusa et al. 2005) and with Chandra as a mosaic of 3×30 ks with an overlapping area of 90 ks (Brusa et al. in preparation). Targets for MAMBO observations were chosen to be un-detected in the X-rays (corresponding to X-ray luminosities $\lesssim 10^{43}$ erg s^{-1}) and with no strong AGN feature in their UV/optical spectra. However, two of the targets (OBJ4415 and 4193) show faint and narrow type2 AGN emission lines in their (almost continuum-less) UV spectra, similar to some of the objects described by van Dokkum et al. (2003). These two objects were not detected at 1.2 mm.

3. OBSERVATIONS AND RESULTS

Each of the five *sBzKs* were observed under predominantly excellent weather on several days during December 2004 with MAMBO–117, at the IRAM 30 m telescope on Pico Veleta. MAMBO operates at an effective frequency of 250 GHz, corresponding to 1.2 mm (FWHM $\approx 10.7''$). The science targets were observed in "on-off" observing mode, which is the photometric mode of MAMBO, for 2700 to 5700 s. This observing technique is based on the chop-nod technique where the target is placed on a reference bolometer element (on-target channel). A detailed description of this now standard observing technique can be found in e.g., Bertoldi et al. (2000); Lutz et al. (2005). In order to reduce systematic errors and avoid spurious detections, the targets were observed several times and on different days. The data were reduced using MOPSIC[12], an upgraded version of MOPSI (Zylka et al. 1998). Every scan with its individual subscans were carefully inspected for the presence of possible outliers or anomalies or influence of high opacity ($\tau_{1.2\ mm} > 0.2-0.3$). From each channel we subtracted the correlated skynoise from the surrounding channels. The outstanding weather conditions – opacity below $\tau_{1.2\ mm} < 0.2$ during 60% of the time – ensured stability and high data quality over the several days in which the data where gathered.

A flux of about 1.3–1.5 mJy (significant at $3.2-3.6\sigma$ level) is detected in the reference bolometers corresponding to the positions of two of the five *sBzK* galaxies (OBJ2742 and OBJ2426; see Table 1). The MAMBO array of detectors consist of 117 bolometers spread over a sky-region of about 4 arcmin in diameter. In order to establish reliably the significance of the detections, and to estimate the likelihood that these may be just be obtained by chance, we independently reduced the observations for each of the 117 MAMBO bolometers. Considering the 5 independent objects observed, this provides a large control sample of about 550 reliable bolometers. Given the source counts at 1.2 mm (Greve et al. 2004), the chance probability to observe a galaxy with flux $\gtrsim 1.5$mJy within half a beam FWHM is 0.6%. However, we assume conservatively that all the control bolometers are seeing a blank mm sky. No control bolometer has a detection with $S/N > 3.6$ (OBJ2426), while 3 control bolometers have $S/N > 3.2$ (OBJ2742). Therefore we conclude that the detections are reliable at better than the 99.5% confidence level. Fig. 1 shows beam sized fields in the B and z band around the two detections.

In order to constrain better the IR-SED of both MAMBO detections, and to further improve the confidence in the detections, we obtained MIPS 24μm imaging data of the field from the Spitzer archive. In the 500s per sky-pixel data, OBJ2742 is detected at a 3 σ level with a flux $S_{24\ \mu m} \approx 70\ \mu Jy$. OBJ2426 is brighter with a flux $S_{24\ \mu m} \approx 200 \pm 50\ \mu Jy$ (the large error being due to the fact that this object is blended with a nearby source $3.5''$ to the west, see Fig. 1, that has a similar 24μm luminosity). The 24 $\mu m/1.2\ mm$ flux ratios for our two *sBzKs* are fully consistent with the range reported by Ivison et al. (2004) for MAMBO galaxies, and also consistent with SCUBA sources (Frayer et al. 2004; Egami et al. 2004).

The two galaxies detected are the ones with the highest estimated SFRs based on the rest-frame UV. No other clearcut differences e.g., color, magnitude, could be found between the MAMBO detected and undetected *sBzK* galaxies. A posteriori, it is reasonable and reassuring that we detect with

[12] http://www.astro.ruhr-uni-bochum.de/nielbock/simba/mopsic.pdf

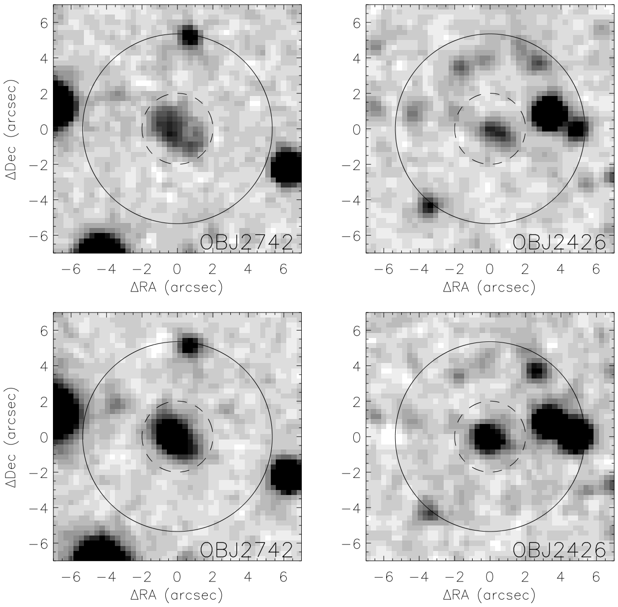

FIG. 1.— B-band (top) and z-band (bottom) images for the fields around the two MAMBO detections (dashed circle): OBJ2742 and OBJ2426. The beam size of MAMBO (10.7″ FWHM, big circle) is fully contained in the images. Both sources show an irregular, possibly merger-like morphology. North is up and east to the left.

MAMBO the 2 sources that were estimated already to be the most active in our sample. This further enhance the confidence that the detections are reliable.

4. DISCUSSION

The fluxes measured at 1.2mm (close to the IR-peak of the dust emission) and at 24μm with Spitzer (in the mid-IR rest-frame region) imply that the two detected *sBzKs* are active IR galaxies. To obtain accurate estimates of their total IR luminosities (8–1000μm) would require further observations between 24μm and 1.2mm, and especially in the range 60–100μm rest-frame, that could constrain the temperature of the dust. For $z = 2$, obtaining these data to the required depths is beyond the possibilities of the available observing capabilities. However, we can derive constraints on the total IR luminosities (and thus SFRs) by assuming these 2 detections have IR SEDs similar to those of well studied $z = 2$ populations, i.e. the average *sBzK* galaxies (Daddi et al. 2005) or SCUBA selected galaxies (Chapman et al. 2005), or by assuming that local empirical correlations between mid-IR or submm luminosities and L_{IR} (e.g. Chary & Elbaz 2001) holds also at $z = 2$. We find that this suggests IR luminosities in the range of $L_{IR} \approx 3$–$10 \times 10^{12} L_\odot$, which correspond to SFRs in the range 500–1500$M_\odot\ yr^{-1}$, the factor of 3 uncertainty being indicative of the range of estimates from the different methods.

We considered the possibility that the detected mm fluxes are due to AGN emission. The submm-to-X-ray spectral slope α_{SX} (Alexander et al. 2003) is an indicator of AGN activity. For the two MAMBO-detected *sBzK*s we derive an upper limit of $\alpha_{SX} \lesssim 1.20$[13] that, if compared to Fig. 7 in Alexander et al. (2003), points toward the starburst part of the diagram occupied, e.g., by SCUBA galaxies in HDFN and Arp 220, and exclude both luminous unobscured (3C273) and obscured quasars. Of course, this does not allow us to completely discard the presence of Compton thick AGNs (NGC 6240). However, the lack of any AGN features in the UV spectra, together with the reasonable agreement between UV- and far-IR- estimated SFRs, suggest that the far-IR activity of these sources is powered by star formation.

An interesting result of our observations is indeed that the IR luminosities and related SFRs inferred for our objects from the mm fluxes are in quite a good agreement, at most a factor 2–3 larger than those estimated from the dust-reddening corrected UV luminosities (Fig. 2, top panel). This agreement, already noticed by Daddi et al. (2005) for the typical *sBzK* galaxy, is somewhat surprising. A fairly different situation seemingly holds for submm/mm selected galaxies (Chapman et al. 2005; Swinbank et al. 2004) and for local far-IR selected ULIRGs (Goldader et al. 2002, with only a notable

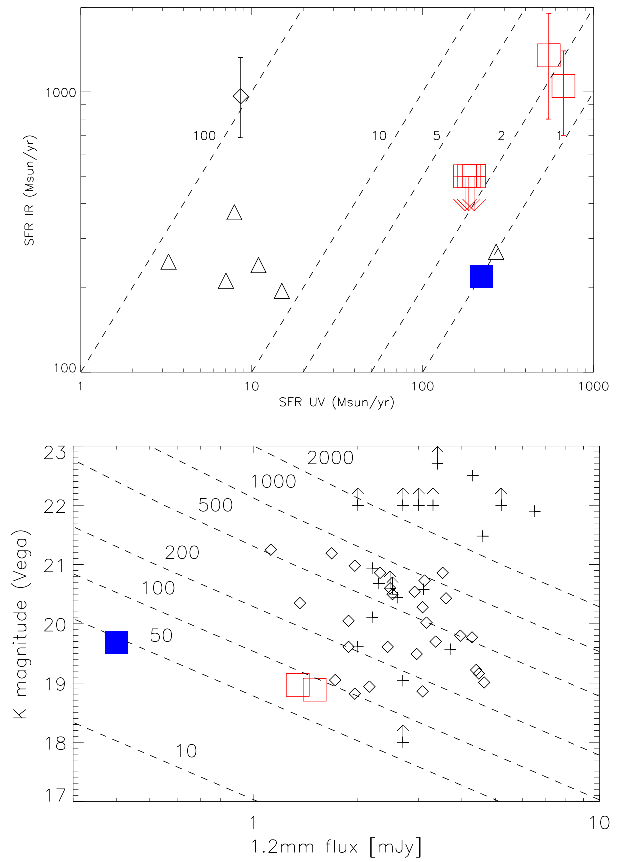

FIG. 2.— *(Top Panel)* SFR_{IR} vs. SFR_{UV} for the five *sBzKs* observed by MAMBO (red open squares). For comparison, we show the median SFR of *sBzKs* from the GOODS-N field (blue filled square; Daddi et al. 2005), a sample of local ULIRGs (open triangles; Goldader et al. 2002; Trentham et al. 1999), and the median for radio-identified SMGs from the SCUBA redshift survey (open diamond; Smail et al. 2004; Chapman et al. 2005). The dashed lines represent different ratios of SFR_{IR} to SFR_{UV} from 1 to 100. *(Bottom Panel)* K-band magnitude (Vega) vs. 1.2 mm flux for our two *sBzKs* detected by MAMBO (red open squares). For comparison, we show the median of *sBzKs* from the GOODS-N field (blue filled square), radio-identified MAMBO galaxies from the NTT Deep Field (crosses; Dannerbauer et al. 2004), and SMGs with $z \geq 1.5$ from the SCUBA redshift survey (open diamonds). The dashed lines represent different ratios of 1.2 mm to K-band flux from 10 to 2000.

[13] We assume ratios of $2.5 - 3$ between 850μm and 1.2 mm fluxes, that are the factors spanned by the models at the luminosities of our objects.

exception), where the observed IR luminosities and far-IR estimated SFRs exceed by 1–2 orders of magnitude the same quantities estimated from the dust corrected UV luminosities (Fig. 2, top panel). Extending this comparison further (Fig. 2, bottom panel), we notice that *sBzKs* galaxies in this paper and in Daddi et al. (2005) are generally brighter in the K band ($\sim 18-20$ mag) than the typical counterparts of MAMBO galaxies (Bertoldi et al. 2000; Dannerbauer et al. 2002, 2004) and SCUBA sources (e.g., Blain et al. 2002; Smail et al. 2004), although they lie at a similar redshift $z\sim 2$. The mm/submm fluxes of SMGs are instead generally higher than those of *sBzKs* (Fig. 2). This implies a significantly different K-band to submm/mm flux ratio between far-IR selected vs. optically selected $z\sim 2$ galaxies.

Similarities also exist between *sBzK*s and far-IR selected populations both in their irregular morphologies (Conselice et al. 2004; Trentham et al. 1999; Daddi et al. 2004a; this paper, see Fig. 1) and in their red observed UV slopes (i.e. high apparent reddening; Chapman et al. 2005; Daddi et al. 2004b; 2005; Goldader et al. 2002; this paper, see Table 1). The differences (submm/mm flux levels, K-band to submm/mm ratios and SFR_{UV} to SFR_{IR} ratios) and similarities (morphologies, UV slopes) are most likely effects induced by the different selection of the samples (K-band versus far-IR), and can be reasonably understood by assuming that the far-IR emitting region of most SMGs is observed behind a thick dust screen, nearly opaque to the optical and near-IR radiation. This can be fit into an evolutionary scenario in which the starburst galaxies are initially deeply embedded into a large column density of dust, during the submm/mm brightest phase when substantial obscuration of a few magnitudes or more is present even at observed K-band (rest-frame $5000-8000$ Å for $z=2-3$). The UV light is almost completely attenuated behind the dust screen so that it is impossible to measure the ongoing SFR from the residual UV light transmitted. As time passes by, SFR and L_{IR} are reduced and the dust is diffused and ejected out of the main star-formation regions (presumably by galactic winds or other kinds of feedback), or simply destroyed. Thus the resulting galaxy is brighter in the near-IR and transparent enough in the rest frame UV that the transmitted light can account for the ongoing SFR after reddening correction. The submm brightest phase has presumably a short duration ($\sim 40-200$ *Myr*; Smail et al. 2004; Greve et al. 2005), while the subsequent *normal sBzK* phase is estimated to last quite longer ($\sim$ 0.5–1 Gyr; Daddi et al. 2005), which would explain why SMGs have a factor of 10 or more lower spatial density (Scott et al. 2002; Daddi et al. 2004a,b), while having similar masses (e.g., Genzel et al. 2003; Greve et al. 2005) and perhaps spatial clustering (Blain et al. 2004; Daddi et al. 2004a; Adelberger et al. 2005). This picture is consistent with the evolutionary scenario proposed by Vega et al. (2005). Chapman et al. (2005) also suggest that SMGs evolve into near-IR bright galaxies.

We conclude by suggesting that the follow-up of the most UV active *sBzK* could be a promising alternative for finding submm/mm sources, possible complementary to the radio pre-selection method presented by Chapman et al. (2001) for a similar redshift range $z\sim 1.5-2.8$, or the Spitzer+MIPS pre-selection (Lutz et al 2005).

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